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A Check on Scaling Laws for Physical Modelling of Geotechnical Freeze-Thaw Effects Using the Centrifuge

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Experimental data collected support the theorized scaling laws that predict that frost heave and thaw settlement in soil developing over one winter can be physically simulated over a matter of hours by freezing and thawing soil while rotating it on the arm of a geotechnical centrifuge. Different soils, ground water levels, and temperature regimes have been physically modelled at different scales. Comparison of an existing Army numerical model of heave in simple soil profiles has shown physical model results to be valuable to calibrate these numerical models for surface heave in silt, but to be less useful for clayey soil. Frost penetration, in contrast, is not predicted well. Tests simulating heave and settlement developing over several years of freezing and thawing, both with and without a buried element have also been conducted.

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1. Manuscripts submitted under ARO sponsorship:

   a) "Centrifuge Modeling of Frozen Soil Effects" by D. Yang and D.J. Goodings (1996) Geotechnical News, the North American chapter magaine of the International Society of Soil Mechanics and Foundation Engineers (March 1996, pp 34-36). (Manuscript sent to ARO)

   b) "Investigation of the Scaling Laws for Centrifuge Modeling of Frost Heave" Dan Yang, PhD dissertation prepared in 1996, to be examined in February 1997. Copies to be sent, when approved, to ARO and CRREL.
   [Two technical articles in final stages of preparation for submission to ASCE technical journals; manuscripts to be submitted to ARO].

   "Centrifuge modelling of cyclic soil freezing and thawing"; Nancy Straub, M.S. thesis is in preparation.

2. a) Scientific personnel supported:

   Deborah J. Goodings, Associate Professor, partial support
   Dan Yang, PhD student, full support
   Jim Lyons, PhD student, full support (AASERT)
   Nancy Straub, MS student, full support (AASERT)

   Marjorie Mewborn, Brian Copley, Christopher Huff, undergraduate assistants, hourly work (AASERT)

   Nora Humphrey and Brian Weir, high school students through 2 summer semesters (AASERT)

   b) Honor/Awards/Degrees: Two undergraduates have received their BS (Civil Engineering). Dan Yang will receive her PhD and Nancy Straub her MS before Summer, 1997.

3. Inventions: None.

4. Scientific progress and accomplishments

The purpose of the work was to collect experimental data of soil freezing and thawing effects from small scale physical models of silt and silty clay, frozen and thawed on the geotechnical centrifuge. The hypothesis is that this technique can be used to simulate correctly the effects of several years of cyclic freezing and thawing, in experiments lasting a few days. The data were to be used to assess the correctness of that hypothesis, and to compare measured soil response to the predictions of the CRREL FROST program. The conclusions of the research are as follow.

a) The similarity of full scale predictions from centrifuge models at three different scales has been striking. This gives evidence to support the theoretical scaling laws and the conclusion that centrifuge modelling of soil freezing is a powerful and reliable research tool for cold regions engineering.

b) Calibration of numerical simulations using one set of data in the CRREL FROST program has proven to produce very good prediction of frost heave in the same soil subjected to different freezing conditions, when the soil is highly frost susceptible silt. The numerical simulation match has been less good for heave in silty clay, which is less frost susceptible, and develops heave in a different manner. In any case, clayey soil was not the type of soil for which the numerical simulation was developed. This does means that centrifuge model data of heave in silts can be valuable to calibrate the CRREL FROST program for engineering design of various configurations and conditions of the same soil when frost heave is at issue. But calibration of the numerical model to mimic depth of frost penetration at the same time as simulating surface heave was not possible in either soil. A sensitivity analysis indicated that the program could not be tuned to achieve this.

Thus, a longer term application of the centrifuge modelling data can be to improve numerical simulation and to broaden its application to other soil types (for example, clayey soils). Model data can also be develop to simulate directly complex engineering configurations relevant to design of civilian and defense structures in cold climates both above and below ground.

5. Technology Transfer:

This work has received significant exposure and input from other Army research engineers throughout its duration. The US Army Waterways Experiment Station is completing construction of the largest geotechnical centrifuge in the United States. It is their expressed intention to use that facility for modelling civil engineering structures relevant to the research and design needs of other Army laboratories, including the US Army Cold Regions Research and Engineering Laboratory and local Corps of Engineers Offices, as well as to make it available, when possible, to non-Army researchers. This research adds significant weight to establishing the validity of cold regions geotechnical modelling on the centrifuge, sample experiments of which they are presently testing.

Initial experimental design benefitted greatly from discussions held at CRREL with Dr. C. C. Smith, then a PhD student at Cambridge University supported in part with research funds from WES, and with CRREL researchers Mr. E. Chamberlain, Drs. R. Miller, S. Ketcham and P. Black. Drs. Ketcham and Black of CRREL have conducted over the same period, high speed small centrifuge models of shallow foundation heave pressures. Interaction between their project and this research has been very advantageous, and results of these two works are consistent. Thin section development and photography were done at CRREL with CRREL's direction. Discussion with CRREL researchers, Dr. R. Berg and Miss S. Biggles regarding the FROST program has clarified various technical questions.

To ensure that Army researchers were aware of this work presentations of this research were made in 1995 to research engineers at WES and CRREL. This has led to further interaction with other CRREL researchers, such as Mrs. K. Henry, about new geotechnical cold regions design questions that may be addressed using the centrifuge. Results of the developing work were presented at the annual meeting of the Frost Effects Committee at the Transportation Research Board of the National Academy of Sciences in 1996, and presented in a poster session at the 1994 International Conference on Centrifuge Modelling held in Singapore. The manuscript described in Section 1 of this report give full documentation of the work. The dissertation and thesis will be distributed to interested CRREL and WES researchers. The journal publications will disseminate the information across the research community.

ROJECT NUMBER: 29555-GS **START**: 18 December 1992

PROJECT TITLE: A Check on Scaling Laws for Physical Modeling of Geotechnical Freeze Thaw Effects Using A Centrifuge

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GOALS: The general goal of this project is to determine whether laboratory centrifuge experiments can be utilized for the physical modeling of frost heave phenomena.

OBJECTIVE: The specific objective of the research is to generate experimental data for small scale physical models that will either support or contradict scaling laws postulated from theory for small scale physical models of freezing and thawing soils. The possibility of using physical model data to calibrate an existing numerical model for design is also examined.

APPROACH: This project utilized a geotechnical centrifuge to study frost heave phenomena under laboratory conditions. The experimental work consisted of two phases, both involving testing models of soil profiles which were frozen and thawed while experiencing acceleration produced by centrifuging. During Phase I, frost heave and frost penetration within the model soil profile were measured under different conditions involving variation in water table location and model scale. In Phase II, the movement of a stone simulating a boulder through the soil profile was tracked during multiple cycles of freezing and thawing.

Uncalibrated predictions using an existing numerical model, developed in part by CRREL, were compared to data of heave and frost penetration collected in two sets of centrifuge physical models. The numerical model was then calibrated to these two, and new predictions were made for behavior of other physical models with other boundary conditions.

RESULTS: In Phase I, two soils, one highly frost susceptible silt and one silty clay of medium frost susceptibility were utilized for the centrifuge modeling. Soils models were constructed to simulate 3m deep soil profiles subjected initially to freezing temperatures for 170 days using three different scales on the centrifuge: (i) model scale 1:20, which required a centrifuge freezing test period of 10.5 hours; (ii) model scale 1:30, which required a period of 4.5 hours; and (iii) model scale 1:45, which required a period of 2.0 hours. Surface frost heave and internal soil cooling were monitored within the specimens during each experimental run. Following each experiment, the scale models were dissected and water content (frozen and unfrozen together) profiles were measured. Thin sections were prepared for photography at USACE-CRREL for

some models. Other freezing regimes simulating slowly changing temperature conditions were also tested.

The similarity of the full-scale predictions derived from the centrifuge experiments at three different scales has been striking. Figure 1 illustrates the similarity of frost heave predictions for models at different scales from one set of frost heave data for silt. Internal similarity of results from soil models of silty clay freezing tests was also very good, but showed a distinctly different pattern of development of heave. These results provide evidence to support the theoretical scaling laws and the conclusion that centrifuge modeling of soil freezing is a powerful and reliable research tool for cold regions engineering.

After calibration using one set of data of model heave in silt in the USACE-CRREL "FROST" numerical simulation program, a very good prediction of frost heave was achieved in the same soil subjected to different freezing conditions. (see Figure 2) The numerical simulation match has been less satisfactory for the prediction of frost heave in silty clay, which is less frost susceptible and, because it develops heave differently, is not the type of soil for which the numerical model was developed. A good match was not achieved for either soil between observed and predicted depths of freezing. A sensitivity analysis of FROST indicated that a good match could not be achieved in the program as it exists at present. The implication of these observations, nonetheless, is that centrifuge model data of frost heave in a silt will be valuable for the calibration of the CRREL FROST program. Because centrifuge model data correctly represent real soil freezing events, they can also be used to develop numerical model simulations involving other soil types (e.g. clayey soils) and other more complex engineering configurations.

In Phase II, centrifuge model tests involved using the most susceptible of the two previous soils to simulate a 4m deep soil profile subjected to 3 years of cyclical freezing and thawing both with and without a buried element simulating a boulder. Scaling laws were applied to the physical model results to test for the similarity of the full-scale predictions to the models built and tested at different scales. This phase is in its final stage of analysis.

IMPACT FOR SCIENCE: Geotechnical centrifuge modeling of soil freeze-thaw effects, now verified for correctness, allows for the expeditious testing - prior to design - of civil and defense structures in contact with soil and subjected to cold climates (especially sensitive structures for which there is no successful design precedent). These structures include buried and surface structures such as pipelines, buried shelters, the foundations of above-ground buildings, roads, and deep shafts. Other dynamic effects such as blast effects in frozen and thawing ground, or the movement of contaminants through frozen or partially frozen ground can also be simulated using a centrifuge model. In addition to direct use for engineering design, it can be used as a tool for development and calibration of numerical models.

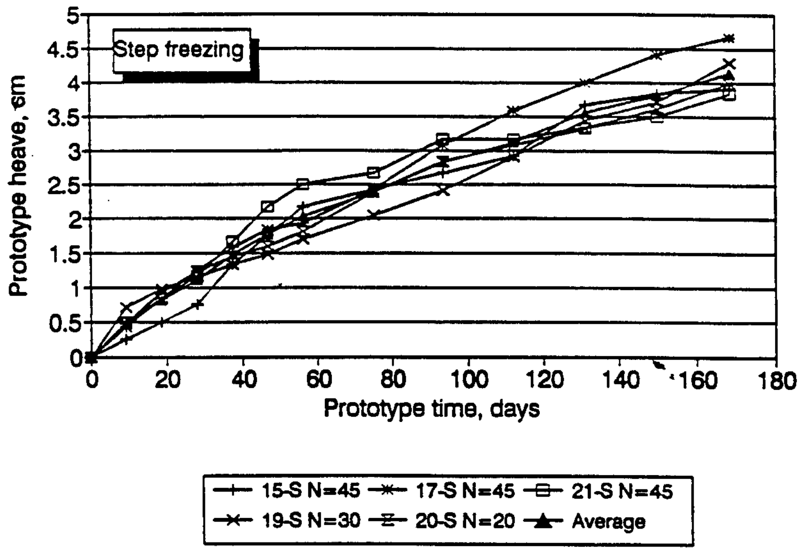


Fig. 1 Heave versus time at prototype scale for step freezing models of silt with high water table

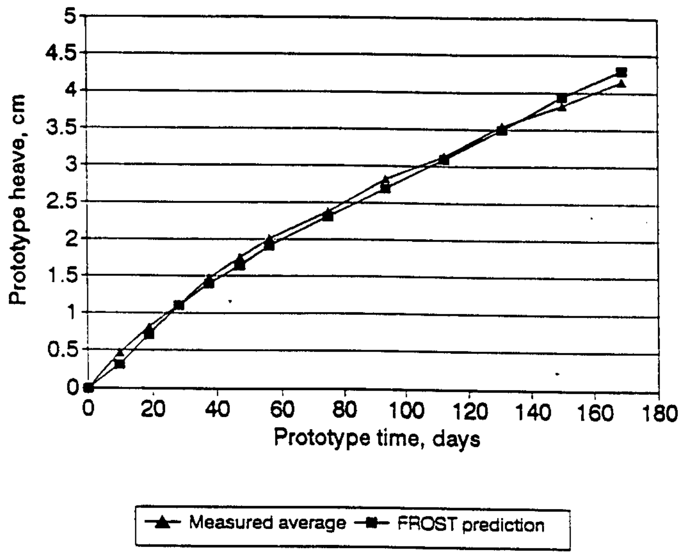


Fig. 2 FROST numerical model prediction shown with measured average of experimental data from Figure 1

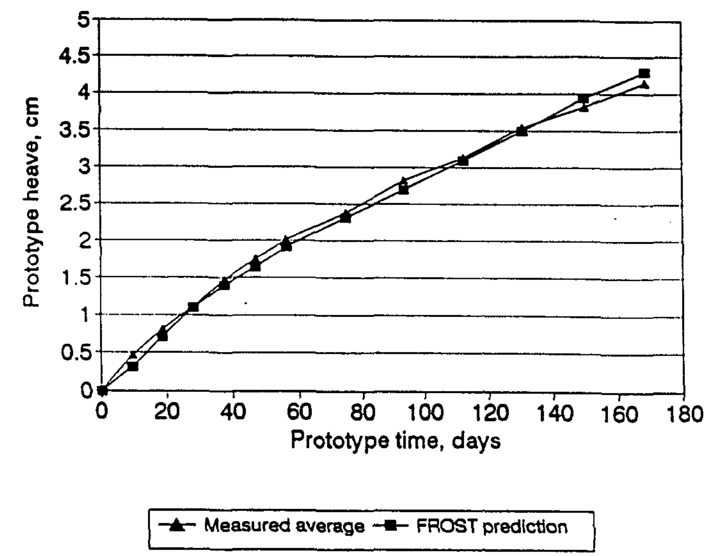
A Check on Scaling Laws for Physical Modeling of Geotechnical Freeze Thaw Effects Using Centrifuge

Performer

- Deborah J. Goodings
  Department of Civil Engineering
  University of Maryland

Goals

- To establish if freezing small soil models for a few hours as they rotate on a geotechnical centrifuge can simulate freezing effects developing over one or more winters; and assess existing CRREL numerical model of soil freezing effects



FROST Numerical Model Prediction and "Measured Average" from centrifuge model data

Objectives

- Conduct centrifuge soil freezing experiments at several scales to assess whether they comply with scaling laws postulated from theory.

- Compare predictions from the CRREL "FROST" numerical model of soil freezing effects to experimental results

Payoffs

Science: Establish validity of physical modeling which allows for much faster collection of data of soil freezing effects and damage.

Army: Established validity of technique for timely design of defense structures in cold climates, especially for which there is no successful design precedent. Centrifuge model data also can quickly be acquired for calibration of CRREL FROST numerical model.